Ferromagnetic Relaxation in Spin Valves With Picoscale Antiferromagnetic Layers

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We have investigated the mechanism of weak exchange bias for a spin valve with threshold layer antiferromagnetic (AFM) thickness using giant magnetoresistance (GMR) and polarized neutron reflectometry (PNR). Results show that the sample exhibits instantaneous switching of the free layer followed by a gradual reorientation of the magnetization in the pinned ferromagnetic layer via domain wall formation. During subsequent field cycles, we found that relaxation in the pinned ferromagnetic (FM) layer is induced not only by an increasing field, but also in a static field over a relatively long time scale.

***Index Terms*—Antiferromagnetic (AFM) materials, giant magnetoresistance (GMR), interface magnetism.**

I. Introduction

THE discovery of giant magnetoresistance (GMR) [1] has prompted the rapid development of spin valves for commercial application, such as hard-drive read heads. A spin valve is a device that exploits the phenomenon of exchange bias, or the coupling of an antiferromagnet to a ferromagnet. This interaction is marked by a hysteresis loop that is shifted off-axis by a value known as the exchange-bias field, as well as an increased coercivity. A simple spin valve typically consists of a free ferromagnetic (FM) layer, a nonmagnetic spacer layer, and a pinned ferromagnetic layer adjacent to an antiferromagnetic (AFM) layer. Exchange bias is currently under a great deal of investigation, as the physical interactions governing the phenomenon are not completely understood. GMR studies at 5 K have verified the presence of exchange bias in spin valves with AFM layers as thin at 0.4 nm [2], indicating origins based in extremely small scale interactions. To uncover the dynamics of such systems at these threshold values, a comparable spin valve with AFM thickness of 0.4 nm is investigated using polarized neutron reflectometry (PNR) and GMR techniques.

GMR measurements offer information regarding the ferromagnetic switching properties of spin-valve samples. Specifically, the exchange and coercive fields may be extracted. A microscopic model of exchange bias requires additional knowledge of the field-dependent switching and magnetization changes of the individual layers, which may be accomplished through PNR studies. Since PNR provides measurements of the depth-dependent vector magnetizations of individual layers on subnanometer length scale, it is an excellent method for probing interfacial coupling and domain wall formation.

Most microscopic models of exchange bias focus on the formation of domains within adjacent ferromagnetic and antiferromagnetic layers, although a recent study by Hoffmann *et al.* [3] focuses on the existence of a small pinned moment in the AFM layer and argues against the formation of domains. In contrast, recent studies utilizing PNR techniques [4] have revealed the formation of a spiral domain wall within the biased ferromagnetic layer.

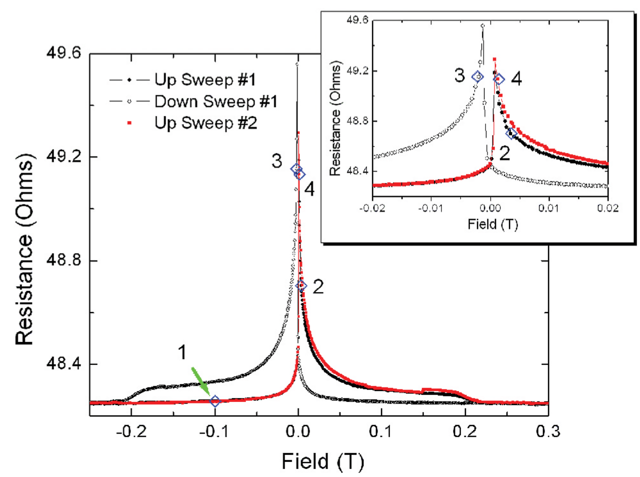

Fig. 1. GMR hysteresis loop with PNR data acquisition points labeled sequentially. Results between ± 0.02 T have been magnified for clarity. (Color version available online at http://ieeexplore.ieee.org.)

II. Procedure

Our sample was grown using direct current (dc) magneton sputtering from metallic targets [5]. Layers were deposited sequentially onto a 1.9-cm^2 silicon wafer yielding the nominal structure of 5.0 nm Ta/3.0 nm $Ni_{80}Fe_{20}$/1.0 nm $Co_{84}Fe_{16}$/3.0 nm Cu/3.0 nm $Co_{84}Fe_{16}$/0.4 nm Ir_{20} Mn_{80}/1.0 nm Cu/5.0 nm Ta. Ta seed layer is used to induce strong (111) texturing. The coupled NiFe/CoFe freelayer leads to low freelayer coercivity and high GMR. The 3.0-nm spacer layer minimizes Neél coupling between the free and pinned FM layers. The CoFe pinned layer insures good pinning with the adjacent antiferromagnetic IrMn layer. The GMR data were collected after field cooling in −0.3 T from 310 to 5 K, with current in-plane, yielding the hysteresis curve given in Fig. 1. The sample exhibits a GMR of 2.1%, but has a negligible value for the exchange field. The

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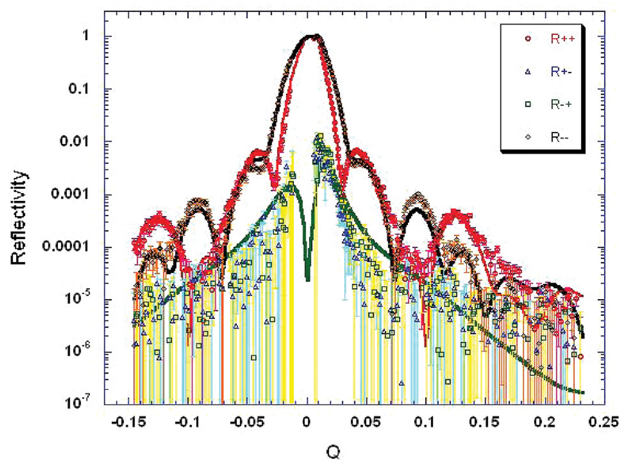

Fig. 2. Reflectivity data collected at 0.0014 T (point 4 in Fig. 1) before relaxation. (Color version available online at http://ieeexplore.ieee.org.)

sharp peaks on the hysteresis loop indicate quick free layer switching, followed almost immediately by a gradual decrease in resistance with increasing field. Such results suggest a slow rotation of the pinned FM layer during field cycling. These results may be compared to more traditional GMR hysteresis curves, which exhibit a square loop during the first generation cycle.

To duplicate the conditions of the resistivity measurements, PNR measurements were taken at 5 K after field cooling in -0.3 T. Neutrons of wavelength 0.475 nm were selected for use in the NG-1 PNR at the National Institute of Standards and Technology (NIST) Center for Neutron Research. The neutrons are polarized parallel to the applied field axis using Fe–Si supermirrors as described in [6]. The resultant reflectivities are corrected for background, efficiencies in the polarizing elements (typically exceeding 96%), and the footprint of the beam. Each data set yields four reflectivity cross sections: $R{++}$ and $R{--}$, designated nonspin flip (NSF) for the neutron's maintained orientation, and $R{+-}$ and $R{-+}$, labeled spin flip (SF), where the neutron polarization axis is rotated by 180°. The NSF reflectivity is sensitive to the chemical structure of the film, and splitting in the $R{++}$ and $R{--}$ cross-sections stems from the component of the magnetization aligned along the field axis. The SF reflectivities originate from the component of the sample magnetization perpendicular to the applied field.

Four independent data sets were collected sequentially at field values of -0.1, 0.0035, -0.0022, and 0.0014 T, labeled as points 1–4 in Fig. 1. The sample was saturated in a field of 0.7 T between the 0.0035 and -0.0022 T measurements, and at -0.7 T between -0.0022 and 0.0014 T measurements. At the 0.0014 T field state, reflectivities were collected from the front and the back of the sample to help detect possible magnetic twists or spirals as described in [7]. X-ray reflectometry measurements were also used to ascertain the complicated structural parameters of our sample. These studies indicated, for example, that the nominal 0.4-nm IrMn layer had an actual width of 0.8 nm due, in part, to limited interfacial interdiffusion and/or local interface roughness. The X-ray values were held constant throughout neutron fitting. In order to obtain a profile for the chemical and magnetic structure as a function of depth, the data were fit using the *Reflpak* software package [8] following the formalism in [6]. Fits were also analyzed for consistency using the genetic algorithm optimization routine [9]. For all fields considered, the neutron fit is most sensitive to changes in the CoFe layer magnetic moments, the magnetic roughnesses, and the magnetization orientation of the pinned CoFe layer. The fits are also relatively insensitive to small moments within the antiferromagnetic layer. Thus our data can neither support or dispute the possibility of pinned spins in the IrMn layer [3].

III. Results

Fig. 2 shows typical reflectivity data obtained at 0.0014 T during the second field sweep (point 4 in Fig. 1). Reflectivity data corresponding to positive wavevector Q was collected from the "front" of the sample, encountering Ta capping layer first, whereas data corresponding to negative wavevector Q was collected from the "back" of the sample, encountering the Si substrate first.

The reflectivity data collected at -0.1 T are similar, but show negligible spin-flip scattering, indicating a parallel alignment of our FM layers with the applied field. This state corresponds to saturation. Note the corresponding low resistance for point 1 in Fig. 1. The fits yield a magnetic moment of 1310 G for the free and pinned CoFe layers and 640 G for the NiFe layer. These values are comparable to bulk expectations; another indication of saturation and the absence of in-plane domains.

The data set taken at 0.0035 T (point 2) during the upward sweep of the first cycle reveals a near parallel alignment of FM layers. Spin-flip scattering is indicative of the formation of a small, parallel domain wall within the pinned FM layer, which accounts for the decreased resistivity of the system. (Note that point 2 in Fig. 1 corresponds to a point of gradually decreasing resistance.) The fits also reveal a 5% decrease in the magnetic moment of the FM layers, an indication of in-plane domain formation. For this sample, the pinned and free layers are not fully aligned antiparallel at the maximum resistance. Instead, parallel domain walls develop during the first field cycle. In contrast, previous studies of exchange-biased systems with thicker AFM layers [4] showed evidence of more extensive pinning during the first field cycle and domain wall formation only after subsequent field sweeps.

During the downward sweep of the first cycle, data were collected at -0.0022 T (point 3 in Fig. 1) after free layer switching had occurred. The orientation of the magnetic layers is very similar to the state at 0.0035 T. The magnetic moment in the pinned CoFe layer has been reduced from bulk by approximately 10%, and the freelayer magnetization matches the saturation value. Fits to the PNR data indicate that the pinned layer is reversing direction through coherent moment rotation. A spiral in the pinned layer spans 30° and, judging from the GMR slope, the spiral persists over a field range of approximately 0.002 T (Fig. 1). Beginning at the AFM/FM interface, the domain wall extends downward through about 75% (2.2 nm) of the ferromagnetic layer.

Data collected during the upward sweep of the second cycle (point 4 in Fig. 1) provides insight into the training effect and magnetic relaxation. Two data sets were collected at 0.0014

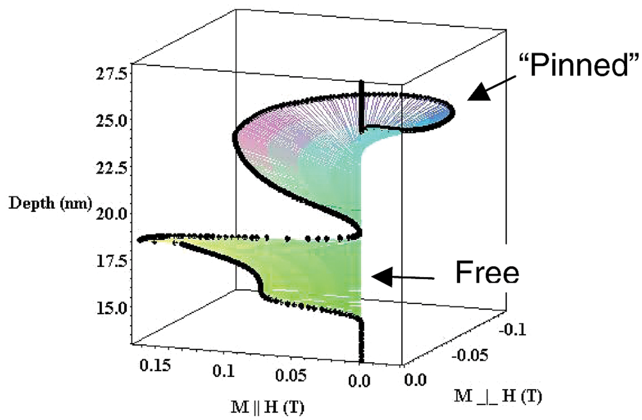

Fig. 3. Initial configuration of the depth-dependent magnetization at 0.0014 T (second-generation field cycle). The parallel and perpendicular magnetization components (in G) are plotted on the x and y axes, respectively. (Color version available online at http://ieeexplore.ieee.org.)

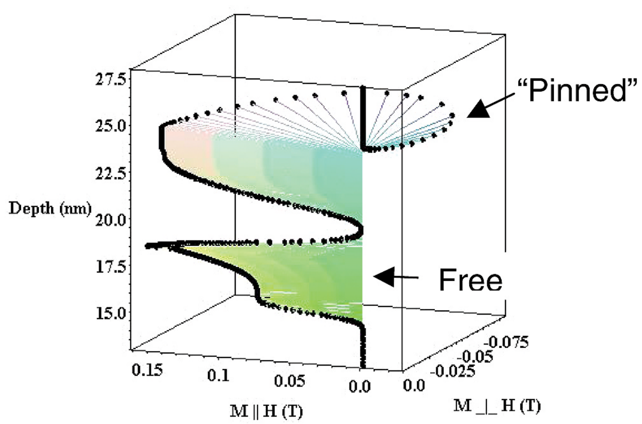

Fig. 4. Depth-dependent magnetization profile at 0.0014 T after relaxation (second-generation field cycle). (Color version available online at http://ieeexplore.ieee.org.)

T, separated by approximately eight hours. Relatively strong spin-flip scattering is observed for the first data set, indicating that the magnetic moment in the pinned FM layer is canted with respect to the applied field. Fits to the data reveal that a large domain wall forms in the pinned layer as shown in Fig. 3. The rotation of the spins spans an angular range of approximately 40°. The fits also indicate that the magnetic moment of the pinned CoFe layer is reduced by approximately 8% from the saturation value, suggesting the presence of in-plane domains.

In contrast, data collected at the same field value approximately 8 h later (Fig. 2), reveal an increased magnetic moment of the pinned CoFe layer, suggesting relaxation back to the saturated state. Further, reduced spin-flip scattering is observed, indicating that the moments in the pinned and free layers are mostly parallel to the field. These results suggest that the magnetic domains have relaxed over time to align with the applied field even though the field has not been increased. Figs. 3 and 4 display the magnetic depth profile of the sample before and after relaxation, respectively. The top colored portion of each picture corresponds to the pinned ferromagnetic layer, and the bottom corresponds to the free layer. Since all other layers in the sample are nonmagnetic, they do not appear in the plot. Note the change in the spiral's pitch and spanned depth. Clearly, the effects of the weak exchange anisotropy at the interface change with time, allowing the entire layer to rotate to a more energetically favorable state.

IV. Conclusion

PNR techniques have been used to probe the consequences of weak magnetic interactions for spin valves with ultrathin AFM layers. The data reveal that the pinned and free layers are not fully aligned antiparallel near the maximum resistance as observed in samples with thicker AFM layers [4], but rather a spiral domain wall develops within the pinned layer during field sweeps. These results account for the rounded hysteresis in the GMR curves and for the negligible exchange bias. Further, we observe that relaxation of the magnetization is induced not only through increasing fields but also over relatively long time scales. In these samples, it thus appears that the coupling between the ultrathin AFM and adjacent FM is only sufficient to pin a small portion of the FM layer. The magnitude and origin of this coupling remain as topics for our future investigations.

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